AN INVESTIGATION OF RF MEMS SWITCHES USED IN WIRELESS COMMUNICATION FOR AIRPLANE CONDITION MONITORING – Reliability and Materials Issues

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Center for Quality Engineering

FAA Centers of Excellence Meeting
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Project Start Date: September 6, 2001
Project Duration: 36 months
Technical Monitor: James Newcomb

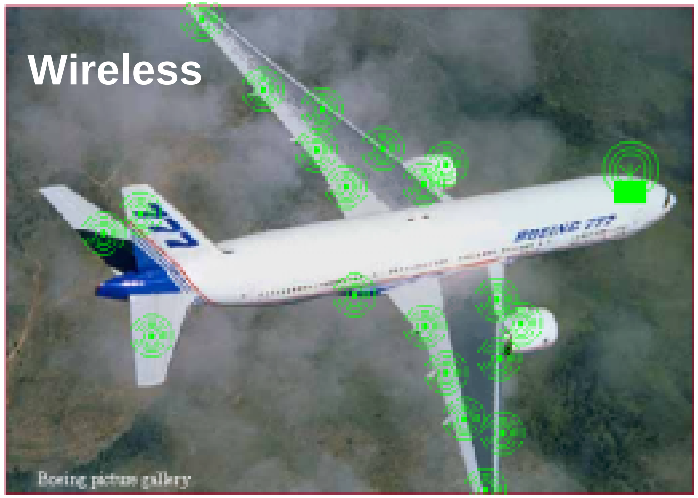
Condition Monitoring of Aircraft Structures

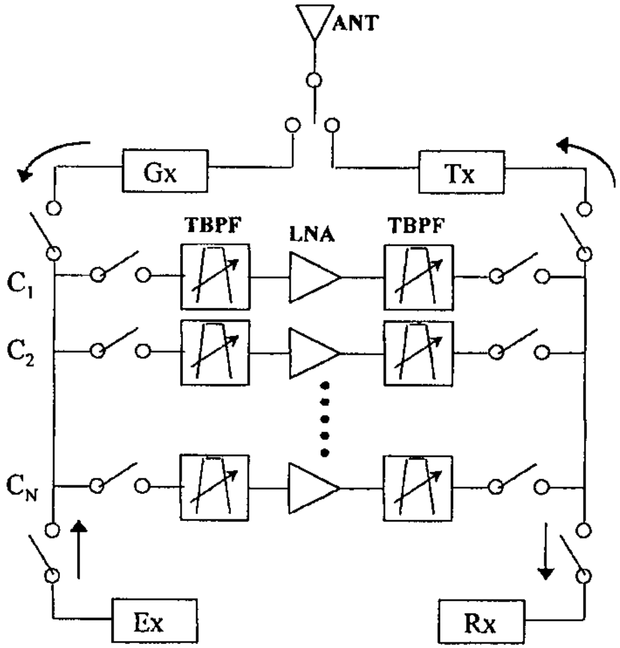
Micro/Nano SENSORS
- Microcracks
- Temperature
- Lubricant Chemistry

Wireless Communication
TELEMETRY

Digital Signal Conditioning and Processing
Real Time
Storage in Memory
Periodic Maintenance

RF-MEMS IN AIRPLANE CONDITION MONITORING

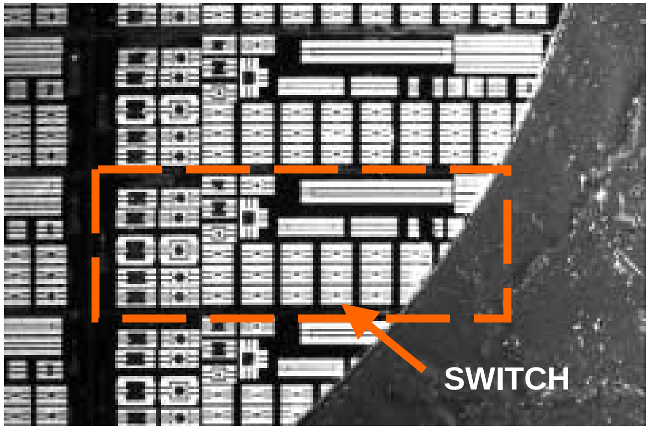


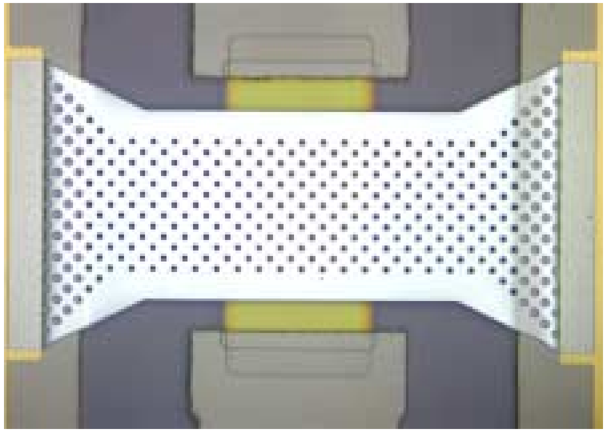


ADVANTAGES:

- **Multiple sensors communicating with a central unit**
- **Modular architecture**
- **Elimination of heavy wiring**
- **RF switches for: Signal routing**
  - **Digitized capacitor banks**
  - **Phase shifting networks**

MEMS for Wireless Communication





- **Applications of RF MEMS Switches**
  - **Wireless RF Communication, e.g., transfer of sensor array information to central unit or satellite-airplane communication for navigation control**
  - **Programmable interconnects**
  - **System network routers**

- **Project Objectives**
  - **Better understanding of emerging NEMS/MEMS Technologies**
  - **Improve reliability of Micro Switches made of Al alloys**
  - **Transition technology to mass commercialization**
  - **Train graduate students and post-docs in the emerging field of Nanotechnology**

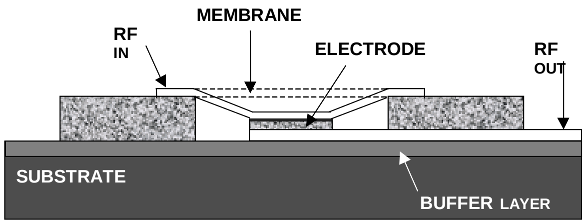
Why Use Micro and Nano Switches

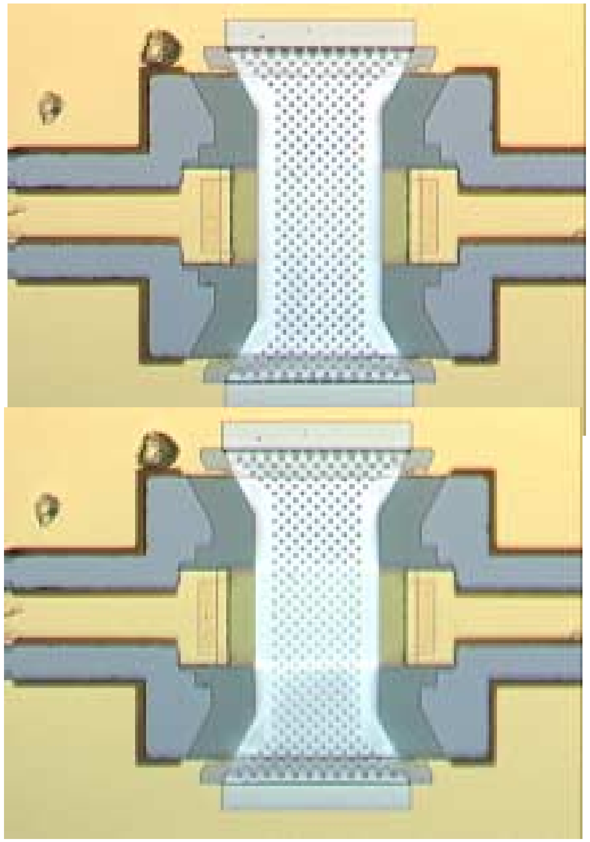
- **Why Micro and Nano Switches?**
  - Major advantages over solid-state counterparts
    - lower insertion losses
    - true on/off state
    - low power
    - no spurious signals

- **Major Commercialization Barriers**
  - Assessing reliability at large number of actuation cycles
  - Effect of temperature on switch response (-30 ^{o}C to 60 ^{o}C)
  - Investigate stiction and relaxation of internal stresses critical to device functionality

RF-MEMS Switch Operation

MEMS Switch

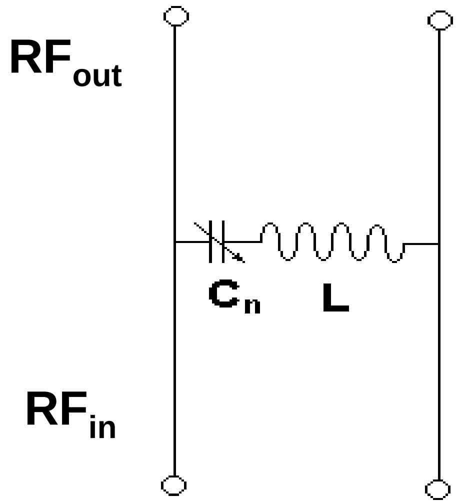




"Off" state

"On" state

- **Switch Operation**
  - Electrostatic actuation pulls membrane to the bottom electrode
  - Capacitive coupling allows RF signal to pass through the bottom RF path



Resonant Frequency

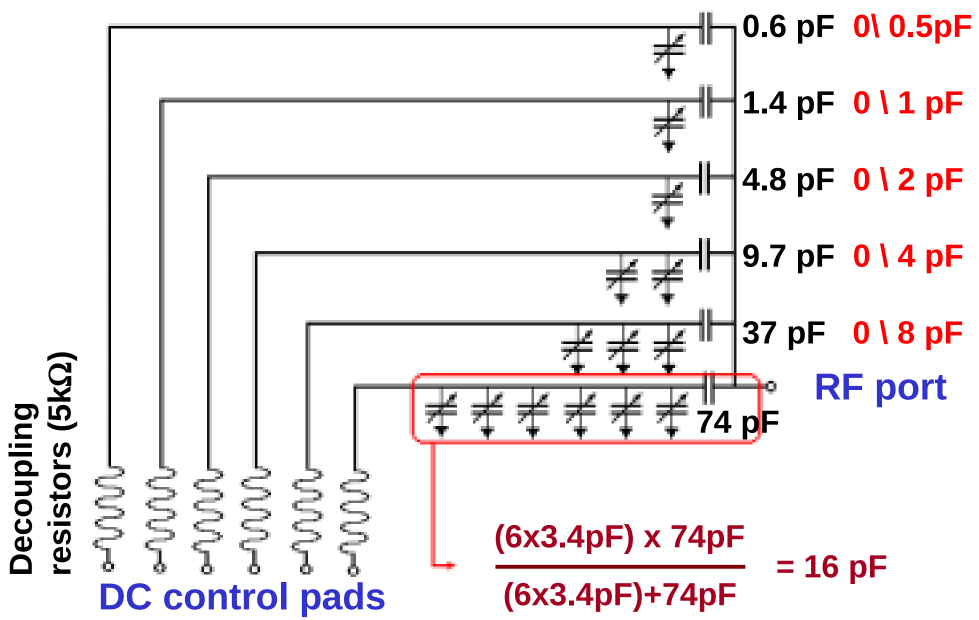
$$F_n = \frac{1}{2\pi\sqrt{LC_n}}$$

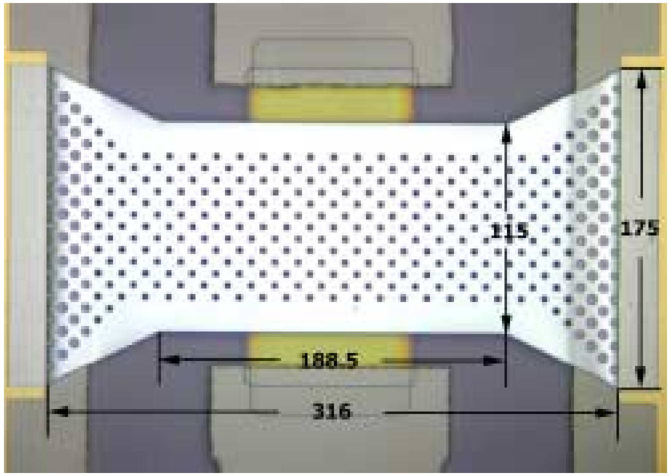
C_n=3.4 pF

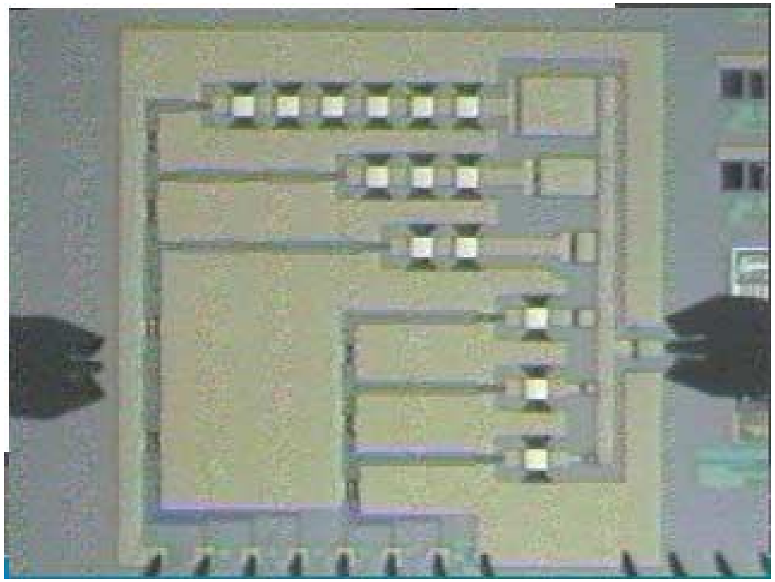
L = 6.5 nH

RF Switch Applications

Tunable Capacitor

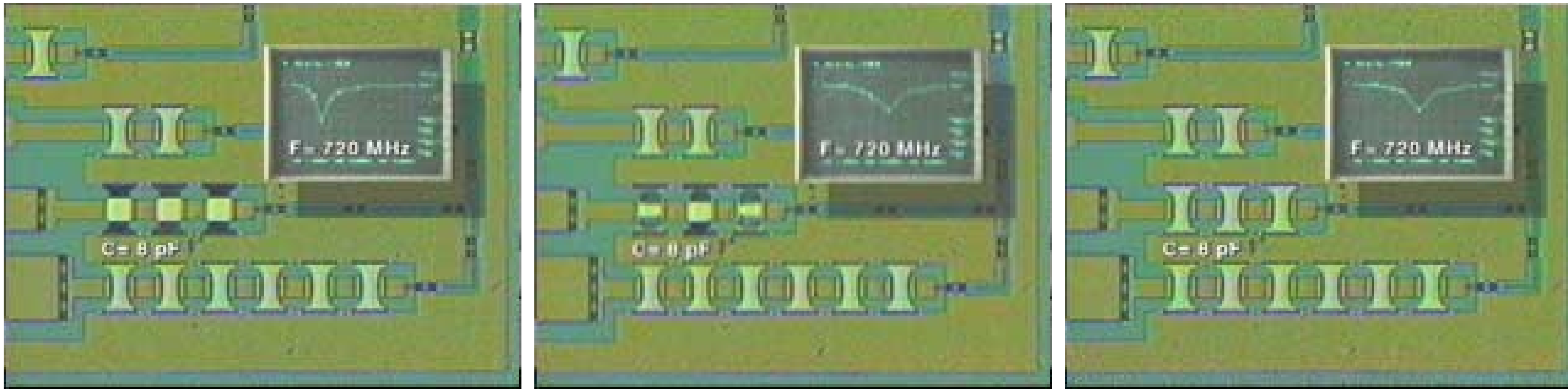




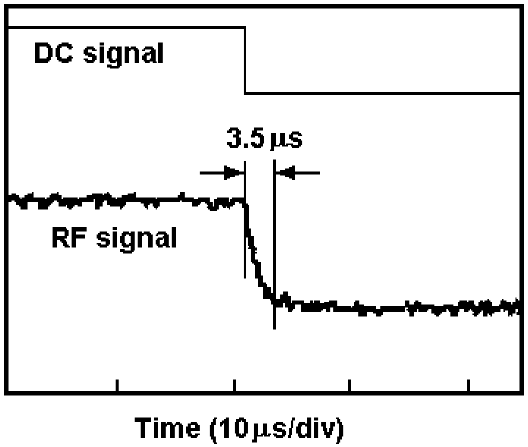


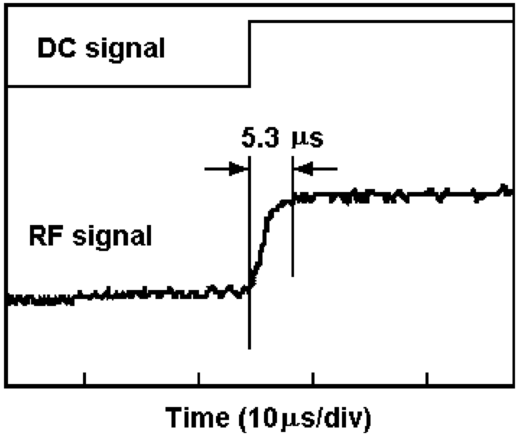
Goldsmith et al., Int. J. of RF and Microwave Computer Aided Engineering, Vol. 9, No. 4, pp. 362-374,1999.

TIME RESPONSE AND EFFECT ON SIGNAL



Switching the DC actuation off/on, not all the membranes recover simultaneously to the initial shape.



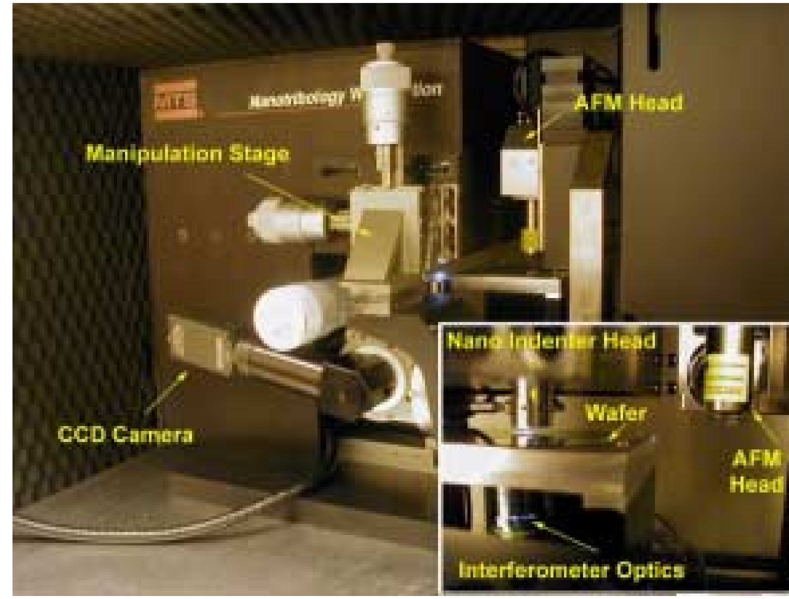


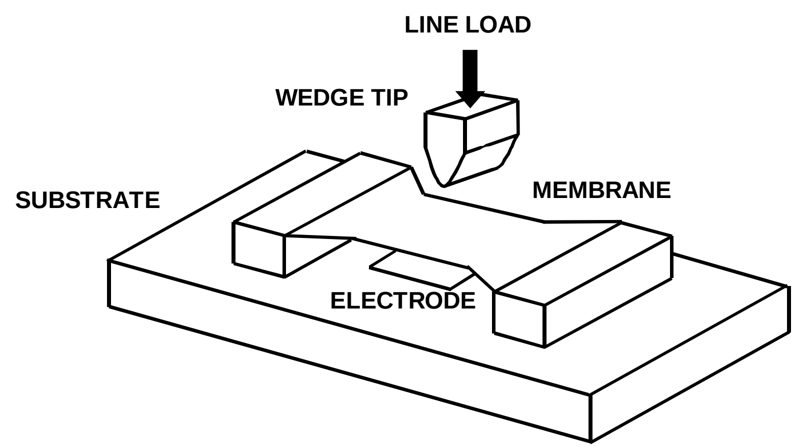
Switching time: ~ 15 µs

(Safe estimate)

MEMS Switch Reliability Testing

- **On-Chip Testing**
  - Deflect membrane with nanoindenter
  - Special wedge tip allows for uniform loading
  - Temperature testing in environmental chamber
  - Load-displacement curves are obtained
- **What do we learn?**
  - E, σ_o, and shape as a function of temperature

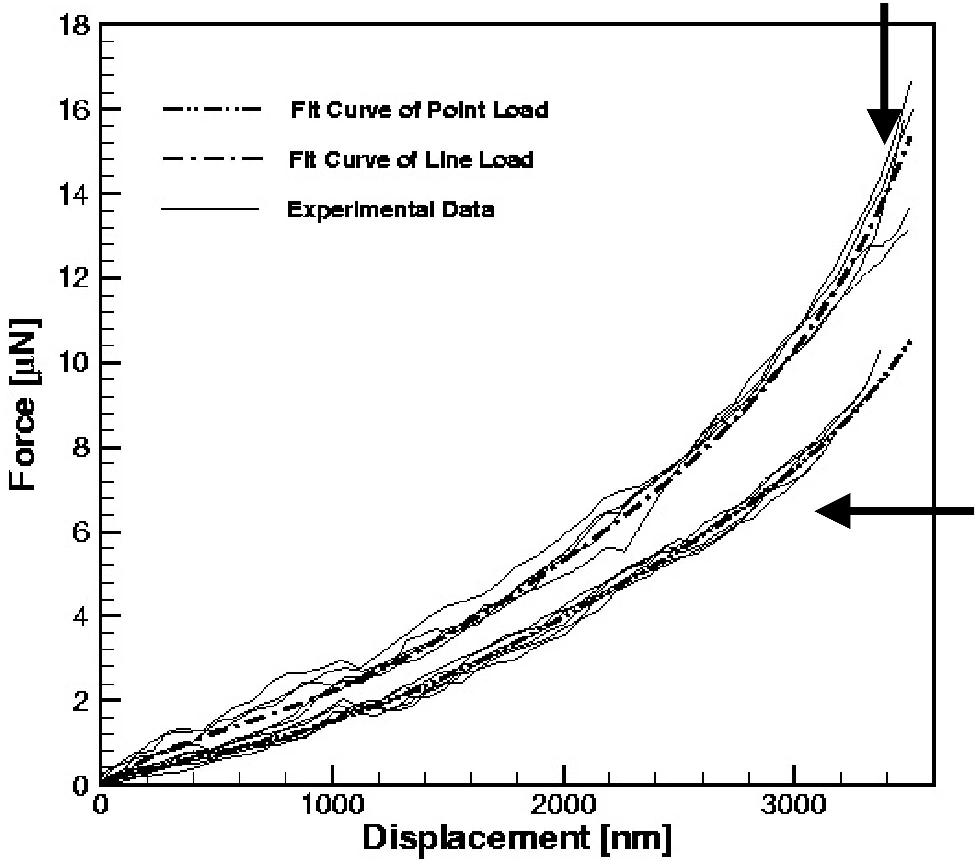




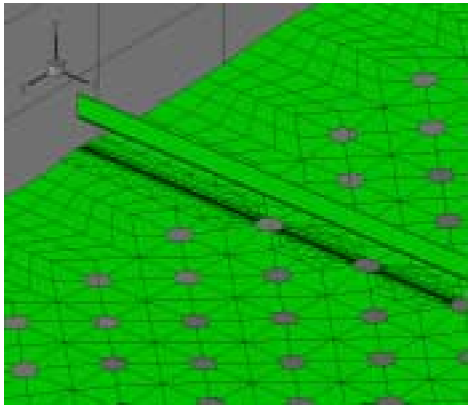
Membrane Deflection Experiment

Experimental Results

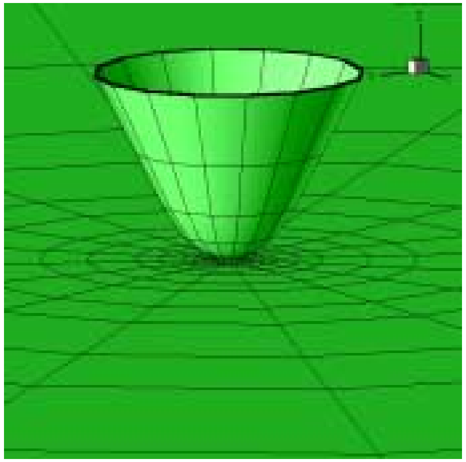
Repeatability



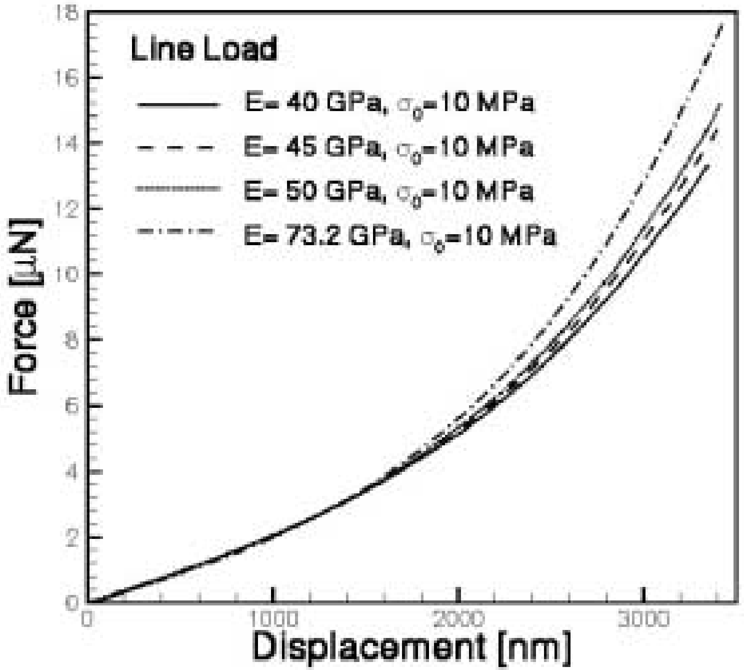
Wedge Tip



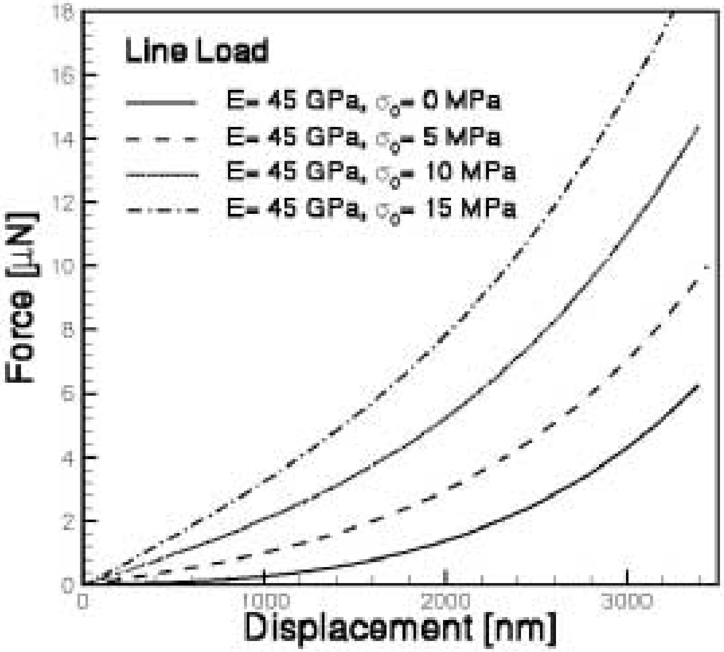
Berkovich Tip



Numerical Simulations



Effect of Young's modulus on load-deflection response

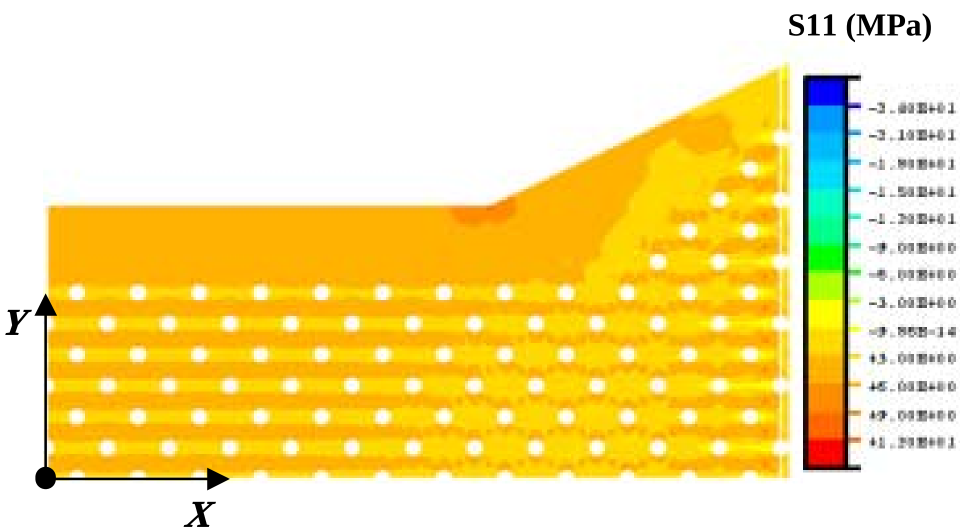


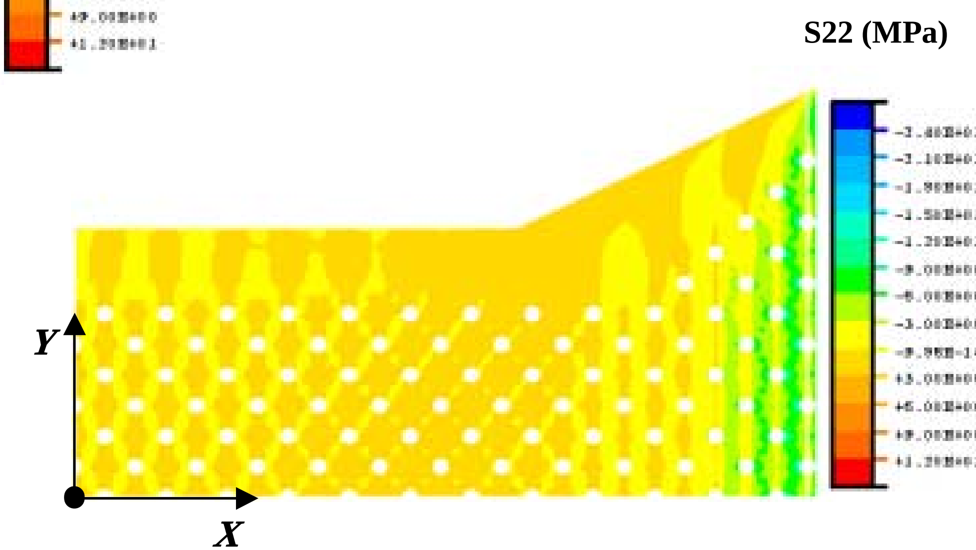
Effect of residual stress on load-deflection response

- **Residual Stress Identification**

Stress Contours

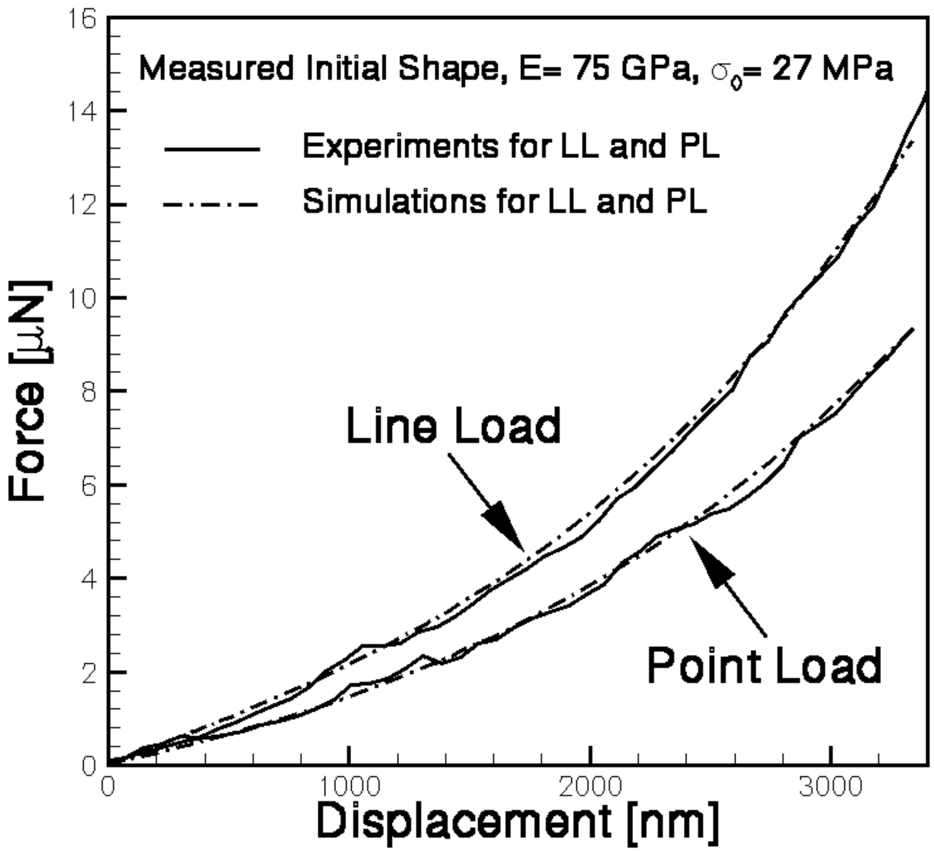
Student: Yong Zhu





Identification at Room Temperature

- **Results of MDE Identification**
  - Experiments
  - FEM simulations accounting for shape, E and residual stress identification

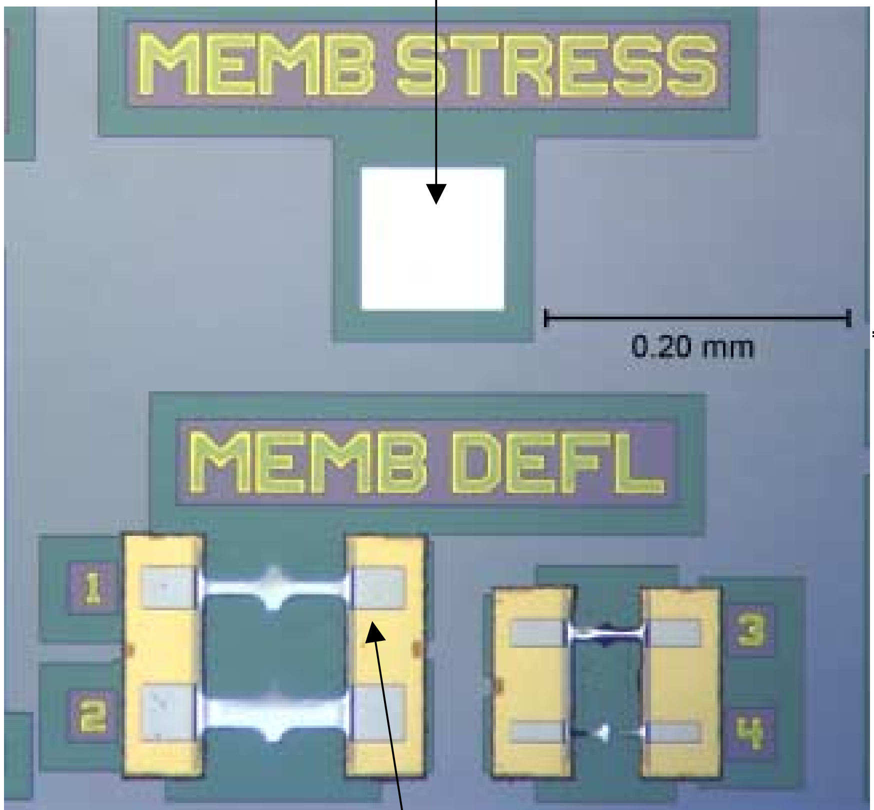


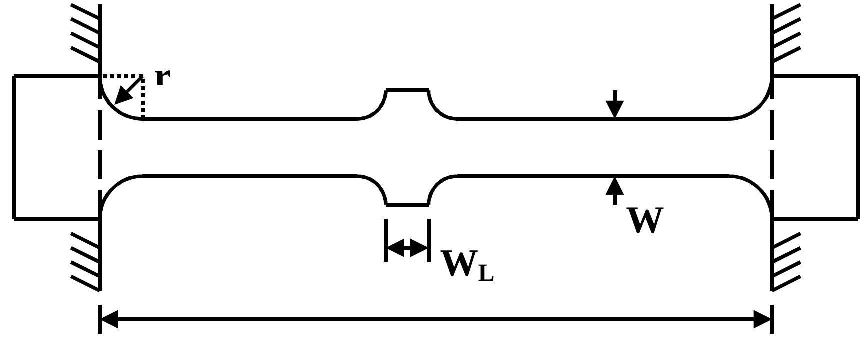
Comparison between experimental measurements and numerical simulations for two indenter geometries. Good agreement is observed for identified set of parameters.

H.D. Espinosa, Y. Zhu, M. Fischer, and J. Hutchinson, "An Experimental / Computational Approach to Identify Moduli and Residual Stress in MEMS RF-Switches," to appear in *Experimental Mechanics*, 2002.

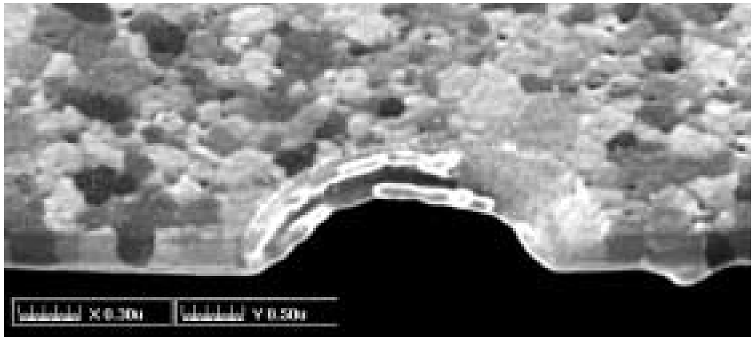
Specimen Shape to Investigate Temperature Effects

Nanoindentation Pad



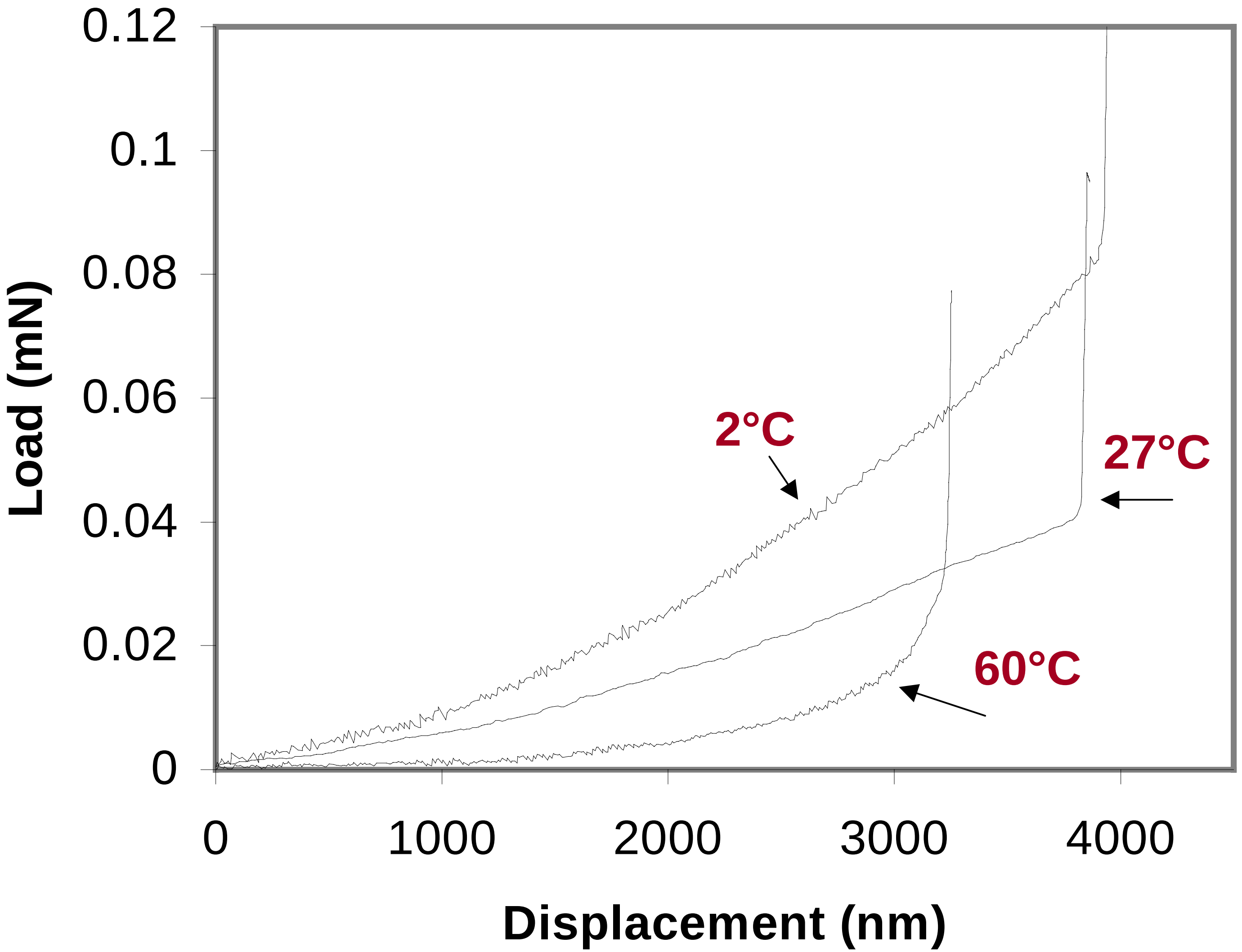


Sample	L (μm)	r (μm)	W (μm)	W_L (μm)
1	100	10	10	10
2	100	10	20	10
3	50	5	10	5
4	50	5	5	5

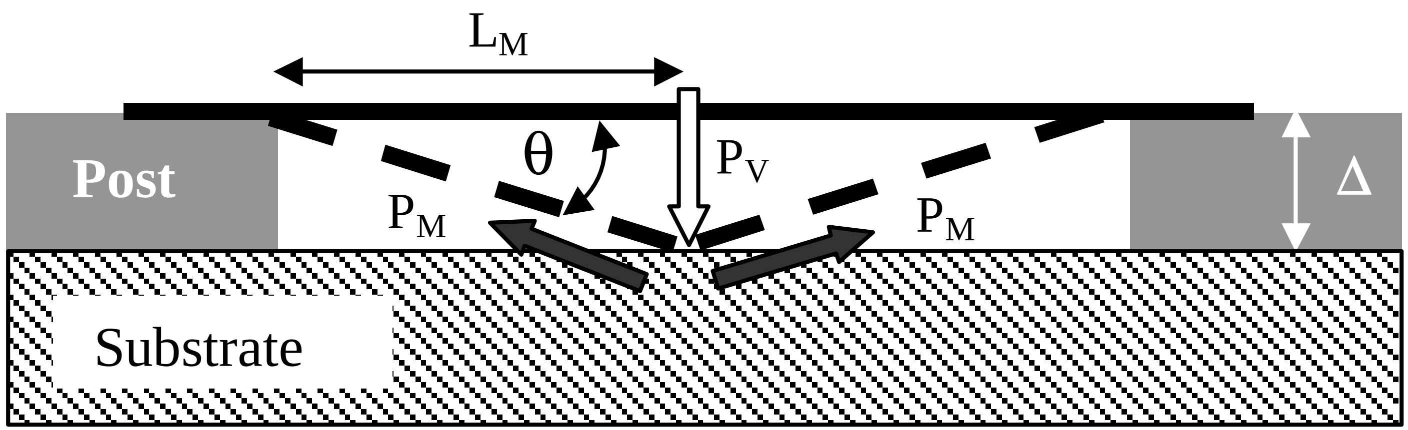


Double Dog-Bone, Freestanding MDE Specimens

Load – Deflection Curves at Different Temperatures



Stress and Strain Calculations



Cauchy Stress

$$\tan\theta = \frac{\Delta}{L_M} \qquad P_M = \frac{P_V}{2\sin\theta}$$

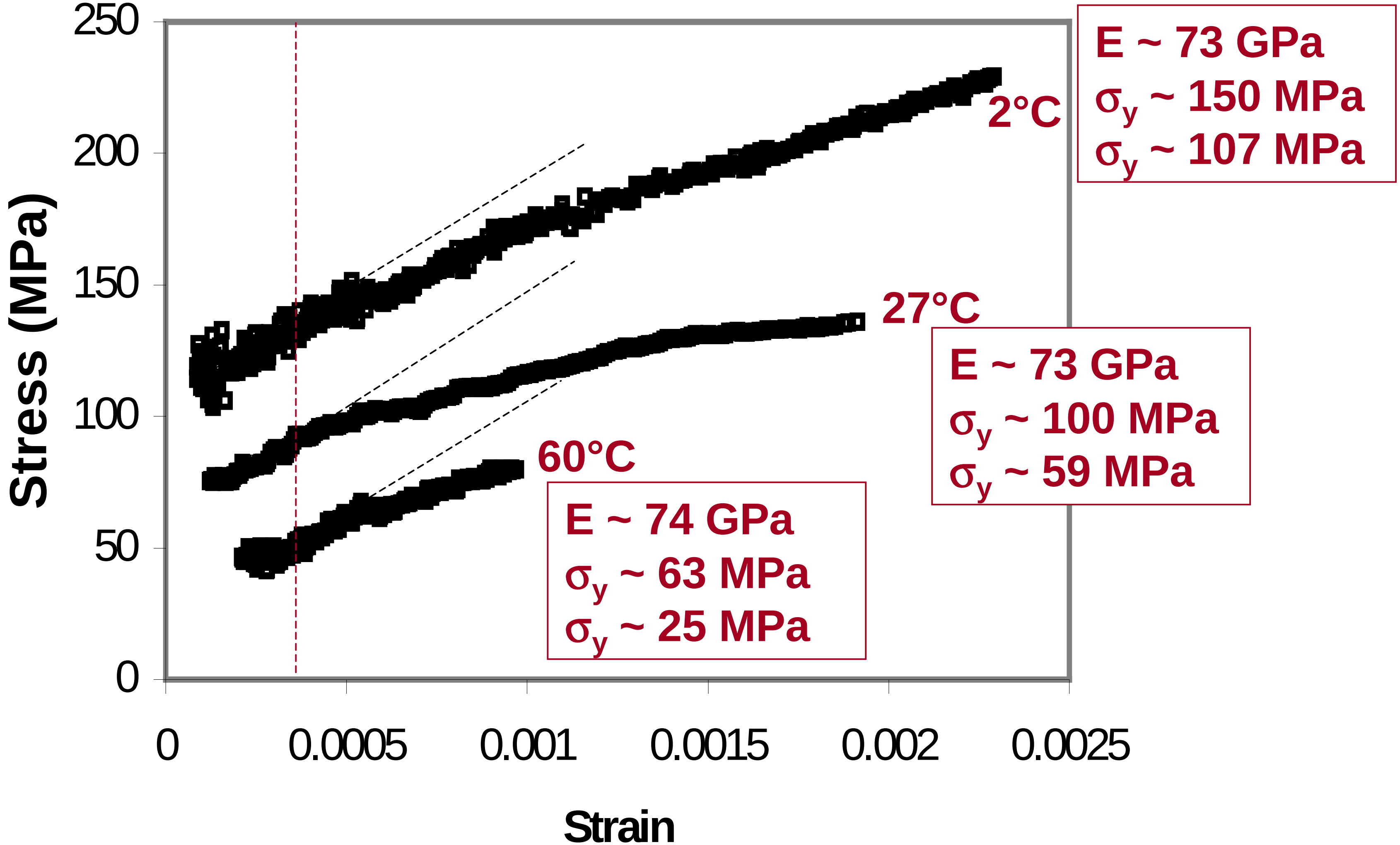
$$\sigma(t) = \frac{P_M}{A}$$

Strain

$$\varepsilon(t) = \frac{\Delta L_M}{L_M} = \frac{\sqrt{\Delta^2 + L_M^2}}{L_M} - 1$$

Stress- Strain Curves

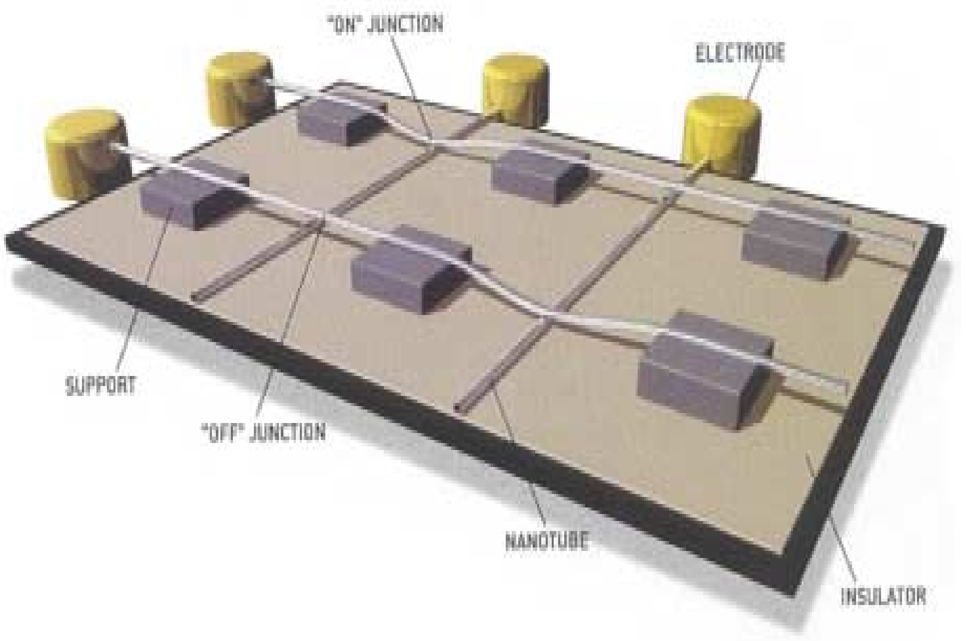
Combined AFM/Nanoindenter



NEMS RF- Switch Concept

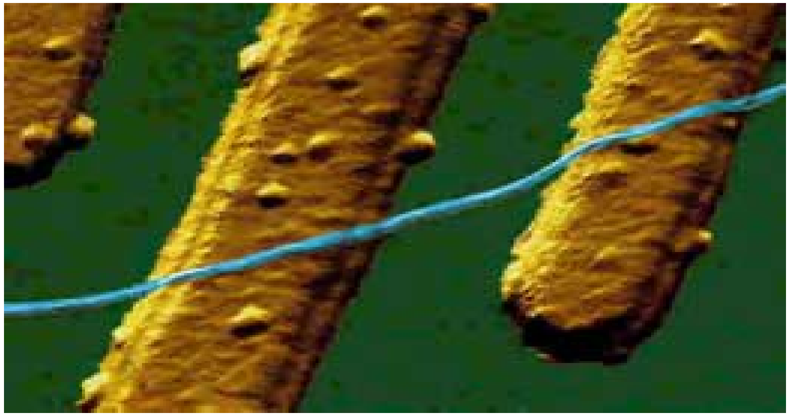
- **CNT Switch Operation**
  - **Electrostatic activation pulls CNT to the bottom electrode**
- **NEMS Switch Advantages**
  - **Time response**
  - **Density of states**
- **Major Challengues**
  - **Nanofabrication**
  - **Electro-mechanical characterization**

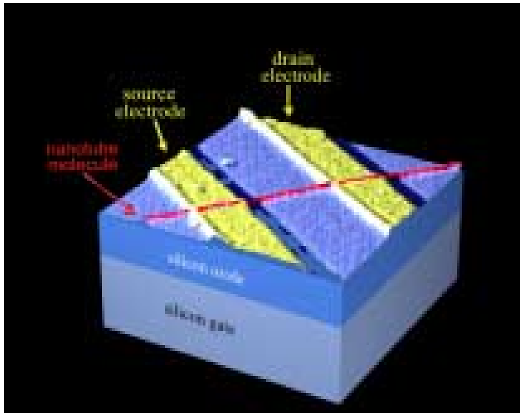
Carbon Nanotube NEMS Switch



Charles Lieber, “The incredible Shrinking Circuit,” Scientific American, September, 2001

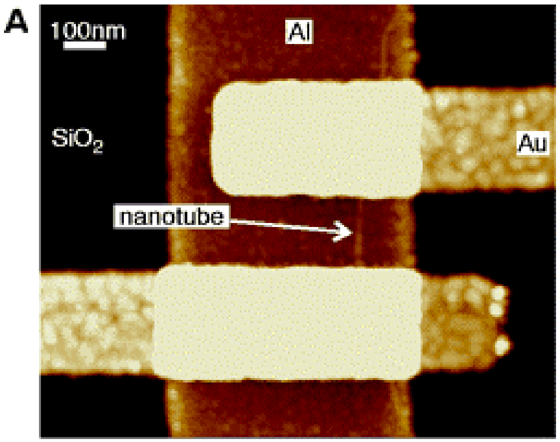
Recent Developments In Nanoelectronics

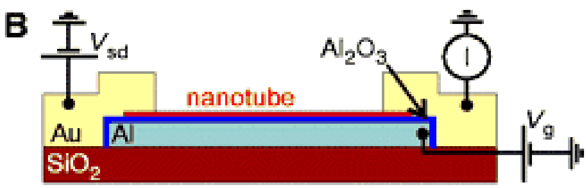


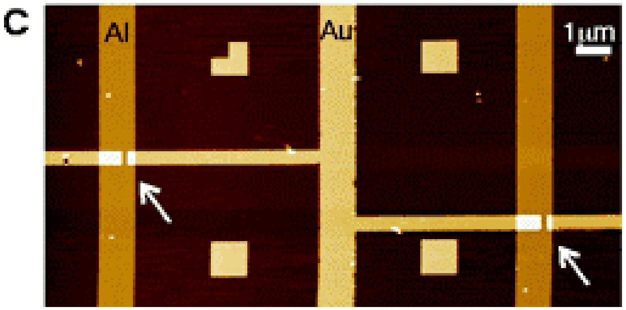


First CNT Single-Electron-Transistor (SET) by depositing of a CNT on top of Au electrodes with SiO_2 as the dielectric layer. Local barrier induced with atomic force microscope (AFM)

Dekker, et al, Science, 2001, 293, 76







Logic Circuit with Carbon Nanotube Transistor

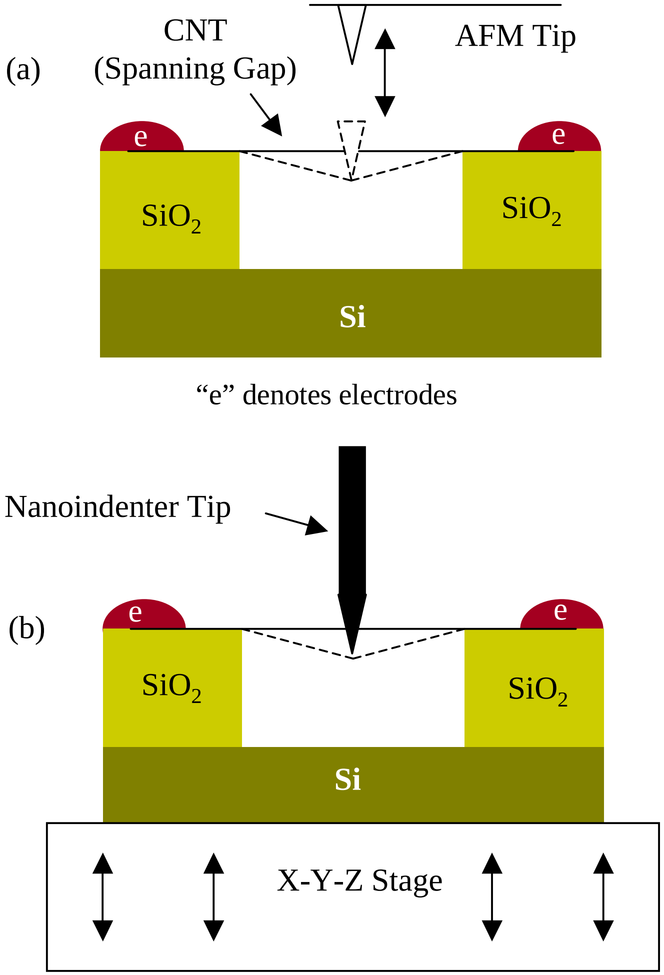
Adrian Bachtold, et al, Science, 2001, 294, 1317

RF-NEMS Switch Testing

Student: C. Ke

- **On-Chip Testing**
  - Deflect CNT with an AFM Tip (a)
  - Deflect CNT with a Nanoindenter (b)
  - Obtain load-displacement curves
  - Measure electrical properties under load and deformation
- **What do we learn?**
  - Young's modulus (E)
  - Changes in conductivity as a function of mechanical deformation

CNT Deflection Experiment



Milestones

- **Quarter 1- 4**

  Initiate Manufacturing of RF-MEMS switches in collaboration with Raytheon System Company. Initiate design of membrane deflection experiment apparatus for low and high temperature testing.
- **Quarter 5-8**

  Obtain Load-Deflection data on aluminum alloy membranes in the temperature range –2 °C to 60 °C. Perform numerical simulations of the membrane deflection experiments to identify moduli and residual stress states as a function of temperature.
- **Quarter 9-10**

  Start experiments to characterize nano-carbon tubes electromechanical response by nanoindentation testing.
- **Quarter 11**

  Finalize assessment of NEMS actuation and impacts on wireless communication technology for the proposed applications of interest.
- **Quarter 12**

  Deliver final project report to FAA.